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Case-study of thermo active building systems in Japanese climate

Rongling Li[a]*, Togo Yoshidomi[b], Ryozo Ooka[c], Bjarne W. Olesen[d]

[a]Department of Built Environment, Eindhoven University of Technology, Eindhoven, Netherlands
[b]Graduate School of Engineering, University of Tokyo, Tokyo, Japan
[c]Institute of Industrial Science, University of Tokyo, Tokyo, Japan
[d]Intl. Centre for Indoor Environment and Energy, Technical University of Denmark, Copenhagen, Denmark

Abstract

Thermo active building systems (TABS) have been applied in office buildings as a promising energy efficient solution in many European countries. The utilization of building thermal mass helps to provide high quality thermal environments with less energy consumption. However, the concept of TABS is entirely new in Japan. This paper introduces and evaluates TABS under Tokyo weather conditions to clarify the potential of use TABS in Japan. Cooling capacity of thermo active building systems used in an office building was evaluated by means of dynamic simulations. Two central rooms of the office were selected for the analysis. Six water control strategies were studied and two of those were found reasonable and suitable for TABS use in Tokyo. These two strategies are: free-cooling using underground heat exchanger combined with TABS and free-cooling with desiccant dehumidification system. For these two cases, the operative temperature was between 22-27ºC during 97~99% of the occupation time. The operative temperature drift was less than 4ºC per day. The pump running time was 7 hours per day and the cooling power of the TABS was 36 W/m2 floor area. For those free-cooling cases, the average supply water temperature was 20ºC, which shows that free-cooling is achievable using underground heat exchangers even considering the temperature increase of the ground during cooling season.

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Keywords: thermo active building systems, free cooling, underground heat exchanger, Japan

* Corresponding author. Tel.: +31 40 247 8577.
E-mail address: R.Li@tue.nl

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1. Introduction

Thermo active building systems (TABS) are water-based heating/cooling systems in which pipes are embedded in concrete slabs of buildings. A prominent advantage of TABS is to reduce the peak load by activating the thermal storage capacity of the concrete slabs. The use of TABS started in the early 1990s in Switzerland [1, 2]. Since the late 1990s TABS has been installed in many new office buildings in central Europe [3, 4, 5]. Since then the trend of using TABS has spread to other parts of Europe, North America and East Asia [6, 7, 8]. In 2005 a series of European standards were provided for calculating design heating/cooling capacity under steady-state conditions of TABS[9], dimensioning and installation[10] and system design based on simple calculations with regards to temperature drift during the occupancy time [3,11]. An ISO standard was published in 2012 for dimensioning and calculation of dynamic heating and cooling capacity for TABS [12].

The reduction of peak load leads to several advantages, for example, reduced investment for the cooling equipment and reduced cost of installation. Rijksen et al. [13] performed on-site measurements and obtained the required cooling power of a building equipped with TABS. It was found that by using TABS the chiller capacity could be reduced by up to 50% compare to air-conditioning systems. An investigation on building thermal mass control showed that cost-optimal control could achieve total cost reductions of up to 13% [14]. A TABS combined with a packaged air conditioning system in residential buildings was simulated by Park et al [8]. It was found that TABS decreased both the heat source energy consumption and the terminal energy use, especially for low-thermal-load buildings.

In buildings using TABS combined with ventilation system, good indoor thermal environment and indoor air quality are expected. Since the ventilation rate is 1 to 2 h^{-1} instead of 4 to 6 h^{-1}, the air draught problem and noise is diminished. A data evaluation of 12 German office buildings shows that those buildings in which the heat was rejected only by TABS using ground cooling or night ventilation provided a good thermal comfort [4]. Measurements and surveys conducted in three schools in the Netherlands found that TABS ensured an acceptable indoor temperature and the users were more satisfied with TABS for heating compared to traditional heating solutions [15].

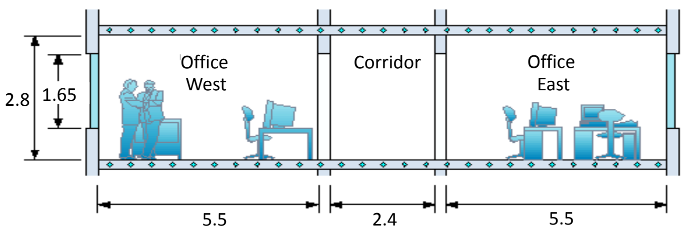
These previous research and on-site evaluations show that TABS is a good solution for energy efficient buildings. However, in Japan it is still an entirely new concept. The possibility of using TABS in Japan is discussed in this paper with dynamic simulations of TABS under Tokyo weather conditions.

2. Methodology

2.1. Building simulation model

The cooling performance and thermal comfort of an office building equipped with TABS are simulated with the dynamical simulation program TRNSYS [16]. Water pipes are embedded in the slabs on all the floors. A central room module in the building with offices on both side of a corridor is selected. The geometrical dimensions of the model are shown in Figure 1; thermal characteristics of the model are given in Table 1. The chosen model is based on research by Olesen et al [6, 7]. The floor area of each office is 19.8 m^2 and the water flow rate of the TABS at each office is 350 kg/h. Simulations are done for the cooling season in Tokyo. Table 2 shows the outdoor design conditions.

Fig. 1. Section of the room module, reproduced from Olesen and Dossi [6]



TABS coupled with a constant air volume (CAV) ventilation system are used in the offices. TABS is switched on during nighttime between 18:00 and 6:00 from Sunday night till Thursday night and operating while room operative temperature exceeds 23ºC. The CAV system operates during office hours from 8:00-12:00 and from 13:00-17:00 on workdays with an air change rate of 1.3 h^{-1}. The supply air temperature is 20ºC and the humidity is 40%. Infiltration is constant at 0.2 h^{-1}.

Table 1 Component properties of the building, reproduced from Kolarik et al [7]

Construction	Components	Thickness [mm]	Density [kg/m^3]	Heat conductivity [W/(mK)]	Heat capacity[Wh/(kgK)]	Emissivity
Floor ceiling	Screed	45	2000	1.4	0.28	0.94
	Acoustical insulation	20	50	0.04	0.42	
	Concrete	180	2400	2.1	0.28	
Outside wall, light	Aluminum	2	2600	200	0.28	0.3
	Insulation	100	30	0.04		
	Aluminum	2	2600	200		
Internal wall, light	Plasterboard	25	900	0.21	0.28	0.82
	Insulation	60	20	0.04		
	Plasterboard	25	900	0.21		
Window Wooden frame, 30%	frame	Heat transfer coefficient = 2.1 W/(m^{2}K)				
	glass	Heat transfer coefficient = 1.1 W/(m^{2}K)				
		Solar heat gain coefficient = 0.58				

Table 2 Outdoor design conditions in summer for Tokyo

Lat. [N]	Long. [E]	Elev. [m]	Dry bulb temperature [ºC]		Humidity [g/kg(DA)]
			Daily max.	Daily min.	
35º41'	139º46'	5.3	34	27.6	19.5

Previous research shows that the cooling of building can be managed with TABS if the peak loads are less than 50 W/m^2 [17]. In this building model, internal heat load of each office during occupied periods is assumed to be 550 W, which corresponds to 27.8 W/m^2; during lunch break (from 12:00-13:00) it is assumed to be 350 W. The windows in the offices are equipped with solar shading device. When the window receives direct radiation, the total shading coefficient of the window is set to 0.5 by using external blinds.

2.2. Water temperature control

Previous research by Olesen et al. [6, 18] found that the water temperature of the pipes should be close to the room temperature for high energy efficiency. Also, supply water temperature should be controlled to prevent condensation in the room. First, some common control strategies [6] for water temperature will be investigated. These strategies are:

C1: $T_{\sup} = T_{dew}$ C2: $T_{\sup} = 22°C$

C3: $T_{av} = 22°C$ C4: $T_{\sup} = 0.52(20°C - T_{amb}) + 20 - 1.6(T_o - 22°C)$

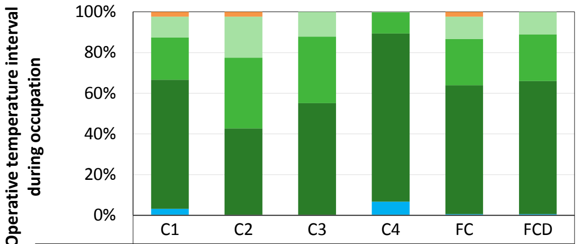
where T_{sup} is supply water temperature, T_{dew} is room dew point temperature, T_{av} is average water temperature of supply- and return water, T_{amb} is ambient air temperature and T_o is indoor operative temperature; all in degree Celsius.

In addition, free-cooling is considered using underground heat exchanger combined with TABS. The supply water temperature is set as 18ºC as the mean annual ground temperature is 17 ºC in Tokyo. The temperature is also limited to the room dew point temperature. Furthermore, desiccant dehumidification system and radiant cooling system is a common combination in Japan as a novel system for low energy buildings. The supply air temperature and humidity of desiccant dehumidifier is commonly 25ºC and 40%. For this scheme, two adaptive control strategies are considered: free-cooling (FC) and free-cooling combined with desiccant dehumidifier systems (FCD).

FC: $T_{sup} = \max(18, T_{dew})$. For free-cooling combined with desiccant dehumidifier systems, some calculation conditions are adjusted as following. FCD: $T_{sup} = \max(18, T_{dew})$, Supply air temperature of desiccant = 25ºC , Operation pump during daytime when $T_o > 26.5°C$.

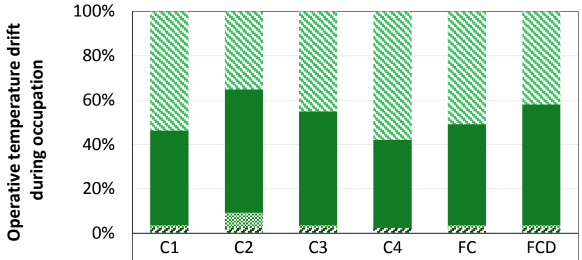
3. Results and discussion

The comfort is evaluated by the hourly mean room operative temperature for the time of occupancy, which is Monday-Friday, from 8:00 to 17:00. The maximum operative temperature allowed for comfort conditions in Tokyo is taken to be 27ºC. The calculated operative temperatures will be compared to the comfort range 22~27ºC, which is given for summer (cooling season) in category C buildings by the standard of ISO 7730 [19]. Furthermore, the evaluation of the results is conducted by means of the cooling season thermal rejection, pump running time, daily thermal rejection and mean cooling power of the TABS.



	C1	C2	C3	C4	FC	FCD
>27°C	2	2	0	0	2	0
26～27°C	10	20	12	0	11	11
25～26°C	21	35	33	10	23	23
22～25°C	64	43	55	83	63	65
20～22°C	3	0	0	7	1	1
<20°C	0	0	0	0	0	0

Fig. 2. Operative temperature intervals during occupation



	C1	C2	C3	C4	FC	FCD
>4°C/day	0	0	0	0	0	0
3～4°C/day	54	35	45	58	51	42
2～3°C/day	43	56	52	40	46	55
1～2°C/day	1	7	1	0	1	1
<1°C/day	2	2	2	2	2	2

Fig. 3. Operative temperature drift during occupation

Figure 2 shows the operative temperature interval during the occupation. The operative temperature for all the cases are within the range of 22~27ºC during more than 93% of occupation time. The operative temperature drift during occupation is within 4ºC for all the cases (shown in Figure 3), which means that the comfort temperature range based on steady-state conditions in ISO 7730 is met [20].

Table 3 shows cooling power of the TABS for all the cases carried out under the weather conditions in Tokyo. The mean pump running hours per day are significantly different among the cases. The longer time means more energy consumption by the pumps. Pump running time for C2 and C3 exceed 10 hours because the supply water temperatures for these cases are higher compared with other cases. Conversely, the water temperature for C4 is low which leads to a short pump running time. However, the water temperature for C4 is even lower than the dew point temperature of the room during most time of the operation which will result in condensation. Thus, C1 is considered the best strategy for water temperature control among C1~C4.

The two adaptive control algorithms of free-cooling (FC) and free-cooling combined with desiccant dehumidifier (FCD) shows similar performance as C1. For these three cases, mean operative temperature during occupation is 24.5ºC, mean thermal rejection by the TABS is between 313~319 Wh/(m^2day) and mean cooling power is 36 W/m^2 floor area. Although the pump running time for FC and FCD is about 1 h/day longer than that for C1, the total energy consumption for C1 would be higher because chillers are necessary for C1~C4. The energy consumption of chillers are usually 3~4 times as much as for the pumps. The pump running time for FCD is 38-hour more than FC, which is due to pump operating during daytime.

Supply water temperature for C1, FC and FCD cases during the cooling season is shown in Figure 4. The supply water temperature for C1 is the room dew point temperature, which vary between 11 and 24ºC. The wide range of the temperature makes this control strategy unpractical. For the whole cooling season the supply water temperature for FC and FCD cases is from 18 to 24ºC, which matches practical supply water temperature of ground heat exchangers in summer in Tokyo. In most time of June and July the dew point temperature is lower than 18ºC, which is the assumed supply water temperature by ground heat exchangers. In August and September, the supply water temperature is mostly higher than 18ºC and up to 24ºC.

Table 3 Cooling power of TABS for all the cases

Water temperature control		C1	C2	C3	C4	FC	FCD
Pump running hours	h	515	980	876	235	604	642*
	h/day	5.9	11.1	10.0	2.7	6.9	7.3
Mean supply water temperature during pump running time	ºC	19.8	22.0	21.3	14.2	20.2	20.1
Mean operative temperature during occupation	ºC	24.5	25.2	24.8	23.8	24.6	24.5
Thermal rejection by the TABS in the cooling season	kWh/m^2 floor area	28	26	27	30	28	28
Mean thermal rejection by the TABS per day	Wh/(m^{2}day)	318	291	304	344	313	319
Mean cooling power of the TABS	W/m^2 floor area	36	33	35	39	36	36
Cooling season: Jun. 1~Sep. 30, 2928 hours; workdays: 88 day; floor area: 19.8 m^2; * including 38h in daytime							

With the additional operation during daytime, FCD achieves a cooler (max To <27ºC) indoor thermal environment. Figure 5 shows the temperatures for FC and FCD during one week from Jul 29 to Aug 5. T_{re} is return water temperature in degree Celsius. During the workdays, the maximum ambient temperature exceeds 30ºC; the maximum operative temperature for FC is 27.5ºC. For FC case, as the indoor dew point temperature is always higher than 18ºC during the night operation time, the supply water temperature equals to the dew point temperature. The room operative temperature for FCD case is less than 27ºC due to the TABS being operated during daytime when the operative temperature is higher than 26.5ºC. In daytime the room dew point temperature is far lower than 18ºC, thus the TABS operated with the supply water temperature of 18ºC. For FC and FCD the supply water temperature was mostly higher than 18ºC, which shows that free-cooling is achievable by using underground heat exchangers even when considering the temperature increase of the ground during cooling season.

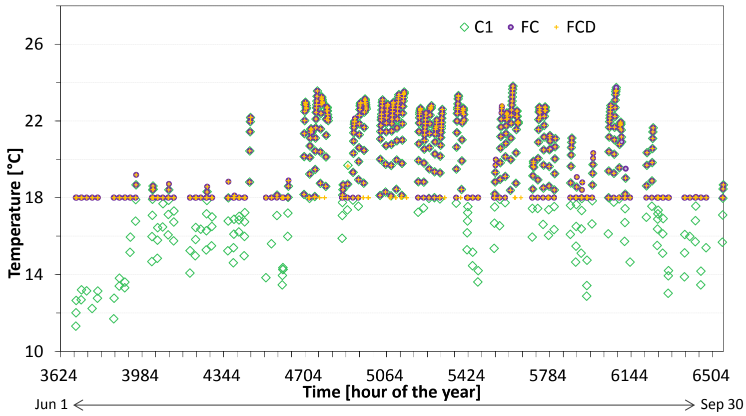


Fig. 4. Supply water temperatures for C1, FC and FCD during the cooling season

4. Conclusions

Office rooms equipped with TABS were simulated under Tokyo weather conditions. Each office has an internal heat gain of 27.8 W/m^2 floor area and 30% glass in the west or east façade. The TABS was activated during night in order to evaluate the performance for peak loads reduction. Two water control strategies were found reasonable and suitable for TABS use in Tokyo: FC, free-cooling using underground heat exchanger combined with TABS and FCD, free-cooling with desiccant dehumidification system. For these two cases, the operative temperature was between 22-27ºC during 97~99% of the occupation time. The operative temperature drift was less than 4ºC per day. The pump running time was about 7 h/day and the cooling power of the TABS was 36 W/m^2 floor area. For the cases of FC and FCD, the supply water temperature was between 18 and 24ºC, which is higher than the mean annual ground temperature of 17ºC. This indicates that free-cooling is achievable by using underground heat exchangers even considering the temperature increase of the ground during cooling season. This case study shows that TABS is capable of providing a comfortable indoor climate during summer in Tokyo.

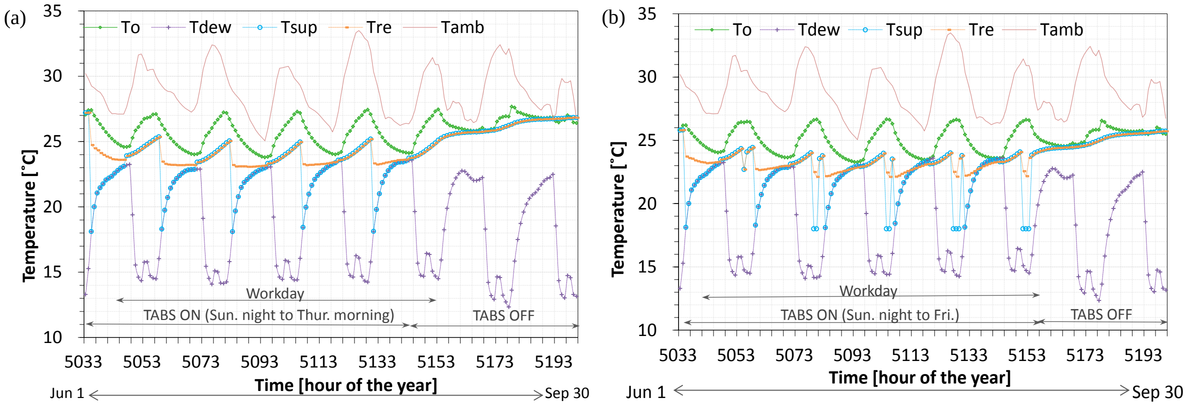


Fig. 5. Temperatures for FC and FCD during one week from Jul 29 17:00 to Aug 5 16:00, (a) FC, (b) FCD

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